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**UNITED STATES PATENT APPLICATION**

**OF**

**SHMUEL PELEG, MOSHE BENEZRA AND ROBERT S. ROSENSCHEIN**

**FOR**

**SYSTEM AND METHOD FOR GENERATING AND DISPLAYING PANORAMIC IMAGES AND MOVIES**

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By

*Richard Jordan*

Richard A. Jordan

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- This application claims the benefit of

## FIELD OF THE INVENTION

The invention relates generally to the field of recording, generating and playing back or displaying images, and more particularly to the generation and displaying of panoramic images stereoscopically.

**\*\*CONTINUING DOMESTIC DATA\*\*\*\*\***  
 VERIFIED PROVISIONAL APPLICATION NO. 60/100,721 09/17/98  
 PROVISIONAL APPLICATION NO. 60/102,720 09/29/98  
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 PROVISIONAL APPLICATION NO. 60/116,138 01/12/99

**BACKGROUND OF THE INVENTION**  
 PROVISIONAL APPLICATION NO. 60/116,139 01/12/99  
 PROVISIONAL APPLICATION NO. 60/123,080 03/04/99  
 PROVISIONAL APPLICATION NO. 60/129,987 04/18/99

Panoramic images are images of a scene having a wide field of view, up to a full 360°. Panoramic images may be recorded using a wide angled lens, a mirror, or the like, providing a wide field of view. Panoramic images having a wider field of view can be generated by, for example, recording a plurality of images around a particular point and, using conventional mosaicing techniques, generating a single mosaic image. Panoramic images may also be generated of simulated scenes using conventional computer graphics techniques.

A problem arises in connection with viewing panoramic images stereoscopically. A person can see stereoscopically because his or her eyes are displaced horizontally (when standing) which, will provide a perception of depth when viewing a scene, which would not be present otherwise. Stereoscopic images comprise two images recorded of a scene recorded from slightly displaced positions, which, when viewed simultaneously by the respective eyes, provides a perception of depth. Although currently there are arrangements for generating and displaying stereoscopically non-panoramic images, currently there are no such arrangements for generating and displaying stereoscopically panoramic images.

## SUMMARY OF THE INVENTION

The invention provides a new and improved system and method of generating and displaying stereoscopic panoramic images.

In brief summary, in one aspect the invention provides a system for generating left and right panoramic mosaic images for use in facilitating panoramic stereoscopic viewing of a scene. The left and right panoramic image generators generate the left and right panoramic mosaic images from a series of images recorded or otherwise generated corresponding to respective angular or other positions, each image having a respective left and right image portion, and mosaics portions of those images together to form the respective left and right panoramic images.

In another aspect, the invention provides a system for displaying a stereoscopic panoramic image to a viewer, by displaying left and right panoramic images such that each is viewed by a respective one of the viewer's eyes.

## BRIEF DESCRIPTION OF THE DRAWINGS

This invention is pointed out with particularity in the appended claims. The above and further advantages of this invention may be better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIGS. 1A and 1B are useful in understanding operations performed by arrangements for generating and displaying stereoscopic panorama images constructed in accordance with the invention;

FIG. 2 schematically depicts a stereoscopic panorama recording and generating system constructed in accordance with one embodiment of the invention;

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1 FIG. 3 schematically depicts a camera used in the stereoscopic panorama recording and  
2 generating system depicted in FIG. 2;

3 FIG. 4 depicts generation of left and right panorama images from images recorded by the  
4 camera depicted in FIG. 1B, useful in understanding the operation of the panoramic image generator  
5 of the stereoscopic panorama recording and generating system depicted in FIG. 2;

6 FIG. 5 depicts a flow chart describing operations performed by the stereoscopic panorama  
7 recording and generating system;

8 FIG. 6 schematically depicts a stereoscopic panorama recording and generating system  
9 constructed in accordance a second embodiment of the invention;

10 FIGS. 7 and 7A schematically depicts a stereoscopic panorama recording and generating  
11 system constructed in accordance with a third embodiment of the invention;

12 FIG. 8 schematically depicts a stereoscopic panorama recording and generating system  
13 constructed in accordance with a fourth embodiment of the invention;

14 FIG. 9 schematically depicts a stereoscopic panorama recording and generating system  
15 constructed in accordance with a fifth embodiment of the invention;

16 FIG. 10 is useful in understanding generation of a stereoscopic panorama image pair using  
17 computer graphics techniques;

18 FIG. 11 schematically depicts a first arrangement for displaying a stereoscopic panorama  
19 image to a viewer; and

20 FIGS. 12A and 12B together schematically depict a second arrangement for displaying a  
21 stereoscopic panorama image to a viewer.

**DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT**

The invention provides systems and methods for generating stereoscopic panoramic images of a scene, and for displaying the images to a one or more viewers in a manner so that the viewer(s) can view the panoramic images stereoscopically. Before describing the inventive systems and methods, it would be helpful to first describe what a stereoscopic panoramic image is and generally how the various systems and methods described herein generate the stereoscopic panoramic images and facilitate their display. This will be done in connection with FIGS. 1A and 1B. With reference initially to FIG. 1A, that FIG. schematically depicts an observer, and, particularly, eyes represented by dots 2L and 2R (generally identified by reference numeral "2L/R") standing vertically and observing a point P in a scene. The observer sees point P by means of rays of light reflected from the point and directed toward the eyes 2L and 2R along respective rays represented by dashed arrows 3L and 3R. It will be appreciated that, since the rays 3L and 3R are not parallel, the observer will be able to observe a depth in connection with the region of the scene at and near point P.

The observer typically can see only a small portion of the 360° panorama around himself or herself. To see more of the panorama, the observer will rotate his or her head in, for example, the direction indicated by the arrow identified by reference numeral 4. Rotation of the head will allow the observer to view other points (not shown) in the scene, along rays (also not shown) that rotate with him or her. If the observer rotates around a full 360°, each eye will revolve around the same viewing circle 5.

It will be apparent from FIG. 1A that each the succession of images as seen by the observer's two eyes as he or she rotates, can be separated into separate sets of images, with one set of images being associated with each eye. This will be described in connection with FIG. 1B. FIG. 1B, depicts the viewing circle 5 divided into separate viewing circles 5L and 5R (generally 5L/R) for the respective left and right eyes, with point P being shown in the same position as in FIG. 1A, with respect to each viewing circle 5L/R, and the associated ray 3L(1) and 3R(1), which correspond to



1 rays 3L and 3R depicted in FIG. 1A. Each viewing circle 5L/R also depicts other rays, identified  
2 by reference numerals 3L(2),..., 3L(N) (generally identified by reference numeral 3L(n)) and  
3 3R(2),..., 3R(N) (generally identified by reference numeral 3R(n)) that represent images that the  
4 respective left and right eyes of the observer will receive of the various points in the scene as he or  
5 she rotates in the direction represented by arrows 4L and 4R.

6 Further in connection with FIG. 1B, to facilitate the viewing of a stereoscopic panoramic  
7 image of the scene by a viewer, the images as would be received by each of the observer's eyes can  
8 be separately recorded and viewed by, or otherwise displayed to, the respective eyes of the viewer.  
9 Thus, if, for example, images are recorded around a circle corresponding to viewing circle 5L at  
10 successive points, in successive direction depicted by rays 3L(1),..., 3L(N), and the images mosaiced  
11 together, and further images are recorded around a circle corresponding to viewing circle 5R at  
12 successive points, in successive direction depicted by rays 3R(1),..., 3R(N), and if those images are  
13 suitably aligned (such that the point of intersection of the rays 3L(n) and 3R(n) are viewed in the  
14 same relative location) and displayed to respective eyes of a viewer, the viewer can see a  
15 stereoscopic panoramic image of the scene.

16 In a similar manner, stereoscopic panoramic images can be generated using computer  
17 graphics techniques. However, instead of the regular perspective projection used in conventional  
18 image rendering, the panoramic image for the left eye will be rendered using rays tangent to a circle  
19 such as viewing circle 5L, and the panoramic image for the right eye will be rendered using rays  
20 tangent to a circle such as viewing circle 5R.

21 The invention provides various arrangements for facilitating the recording of images from  
22 which left and right panoramic images can be generated, which, in turn, can be displayed to a viewer.  
23 Generally, left and right panoramic images can be generated by rendering from a model, or by  
24 recording a plurality of non-panoramic images and mosaicing together portions thereof to generate  
25 the left and right panoramic images. While in FIG. 1A, the eyes are depicted as viewing in a

1 direction tangent to the viewing circle 5, it will be appreciated that in some embodiments the camera  
2 may instead be generally, although not precisely, perpendicular to the viewing circle.

3 FIG. 2 schematically depicts a stereoscopic panorama recording and generating system 10  
4 constructed in accordance with one embodiment of the invention. With reference to FIG. 2, system  
5 10 includes a camera rig 11 and a panorama mosaic image generator 12. The camera rig 11 includes  
6 an image recording device such as a camera 13 mounted on a support comprising an upwardly (in  
7 the case of horizontally-recorded panoramas) extending mast 14 and an arm 15 rigidly affixed  
8 thereto and extending therefrom. The camera 13 may record images using any of a number of types  
9 of image recording media, including, for example, film, charge-coupled devices (CCD's) or the like.  
10 The camera 13 is rigidly mounted on the arm 15 so that the images recorded by the camera 13 will  
11 be recorded thereby a predetermined distance from the mast 14. A motor 16 is configured to rotate  
12 the mast 14 around a vertical axis, thereby to, in turn, cause the camera 13 to revolve along a curved  
13 path centered on the axis around which mast 14 rotates. The movement of the motor 16 is controlled  
14 by a motor control 17 which, in turn, is controlled by the panorama mosaic image generator 12, as  
15 will be described below. Since the camera 13 is rigidly affixed to the arm 15, the camera 13 will  
16 point in a direction defined by the arm 15. In one embodiment, the camera 13 is a still camera, as  
17 opposed to a motion picture camera, and in that embodiment the motor 16 will preferably be a  
18 stepping motor to enable the camera 13 to revolve step-by-step, with the camera 13 being stopped  
19 at each step to allow the camera 13 to record an image. In that case, the angle between steps will be  
20 such as to facilitate mosaicing images recorded at each step into a panoramic image, as will be  
21 described below in connection with FIGS. 2 and 3. At some point, each of the images recorded at  
22 successive steps will be provided to the panorama mosaic image generator 12 for processing. The  
23 panorama mosaic image generator 12, in turn, receives the images recorded at the successive steps  
24 and mosaics portions of the images together to generate therefrom a stereoscopic panoramic image  
25 pair comprising left and right panoramic images. The left and right panoramic images comprising  
26 the stereoscopic panoramic image pair may be displayed to or viewed by a user as will be described

1 below in connection with FIG. 3 to provide the user with a stereoscopic image of the scene as  
2 recorded by the camera 13.

3 As noted above, the panoramic image is generated by mosaicing together portions of images  
4 recorded with the camera 13 at various angular positions around the center of rotation of the mast  
5 14. Before proceeding further, it would be helpful to describe details of the camera 13 and how the  
6 panoramic image generator 12 mosaics portions of the images together to form a panoramic image  
7 pair that, when viewed simultaneously by an observer's left and right eyes, provides a unitary  
8 stereoscopic panoramic image of the scene surrounding the location of the mast 14. FIG. 3 is a top  
9 plan view depicting details of the interior of camera 13, as seen from the top in FIG. 2, and FIG. 4  
10 depicts details of images recorded by the camera and how portions of those images are mosaiced  
11 together to form the stereoscopic panoramic image pair. With reference initially to FIG. 3, camera  
12 13 includes a housing 24 having a forward aperture 20, a rear image recording medium 21, a screen  
13 22 proximate to and forward of the image recording medium 21, and a shutter 23. The image  
14 recording medium 21, which defines an image plane for the camera 13, may comprise any  
15 convenient image recording medium, including film, a CCD array, or the like. The camera 13 may  
16 also include a lens (not shown) in the aperture 20 to facilitate focusing of images on the image plane.  
17 Alternatively, the camera 13 may comprise a pinhole camera, in which case no lens will be provided.

18 The shutter 23 is provided to selectively allow light reflected from portions of a scene 27 at  
19 which the camera 13 is directed is allowed to enter the camera and project upon the screen 22 and  
20 portions of the image recording medium 21 for recording thereby. The scene 27 forms part of a  
21 panoramic scene which is centered on the axis of rotation of the mast 14. Preferably, the shutter 23  
22 will be closed while the motor 16 moves the camera 13 from one step to the next, thereby to block  
23 light from the scene 27 from entering the camera 13 and exposing the image recording medium 21  
24 during such movement, which might otherwise cause blur in the recorded image. After the motor  
25 16 has reached a next step and the camera 13 has stopped moving, the shutter 23 can be opened to  
26 allow light from the scene 27 to enter the camera and be directed rearwardly toward the screen 22





1 and image recording medium 21. After the image recording medium 21 has been appropriately  
2 exposed, the shutter can be closed, and the motor 16 energized to rotate the mast 14, thereby step  
3 the camera 13 to a new orientation, at which point these operations can be repeated. Preferably, if  
4 the image recording medium 21 is film, the film will be advanced before the shutter 23 is again  
5 opened so as to avoid double-exposure; similarly, if the image recording medium 21 is a CCD  
6 device, the image information can be retrieved and stored and the CCD's refreshed as necessary to  
7 avoid double exposure. The image recorded by the camera 13 at the respective steps will be  
8 independent of each other, so as to avoid multiple exposures.

9 The screen 22 is configured to generally cover portions of the image recording medium 21,  
10 except for at least two vertical slits 25L and 25R, which allow light from respective directions and  
11 portions 27L and 27R of the scene 27 to fall on proximate regions 26L and 26R of the image  
12 recording medium 21 and be recorded thereby. As is shown by the dashed lines 28L and 28R, the  
13 slit 25R is positioned to allow region 26R of the image recording medium 21 to record the left-hand  
14 portion 27R of the scene 27, and the slit 25L is positioned to allow region 26L of the image  
15 recording medium 21 to record the right-hand portion 27L of the scene 27. With reference to FIG.  
16 1A, it will be appreciated that the portion 27R of the scene 27 as recorded by the region 26R of the  
17 image recording medium 21 is from a direction which corresponds to the direction that an observer's  
18 right eye would be viewing that portion 27R of the scene if he or she were looking directly at the  
19 portion 27R of the scene. Similarly, the portion 27L of the scene 21 as recorded by the region 26L  
20 of the image recording medium is from a direction which corresponds to the direction that the  
21 observer's left eye would be viewing that portion 27L of the scene if he or she were looking directly  
22 at the portion 27L of the scene. It will further be appreciated that, preferably the placement of the  
23 camera 13 on the arm 15 will be such that, as the camera 13 is rotated, the regions 26L and 26R  
24 revolve through a circle, namely, the image circle, and the rays shown by dashed lines 28L and 28R  
25 are tangent to an inner viewing circle similar to that described above in connection with FIGS. 1A  
26 and 1B. Thus, as the motor 16 steps the camera 13 so as to enable the region 26L of the image  
27 recording medium 21 to record what is depicted in FIG. 3 as portion 27R of the scene 27, an

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1 observer who contemporaneously views that image with the left eye, and with the right eye the  
2 image previously recorded in the region 27R of the scene 27, would see a stereoscopic image of that  
3 portion 27R of the scene 27. Similarly, when the motor 16 steps the camera 13 so as to enable the  
4 region 26R of the image recording medium 21 to record what is depicted in FIG. 3 as region 27L of  
5 the scene 27, an observer who contemporaneously views that image with the right eye, and with the  
6 left eye the image previously recorded in the region 27L of the scene 27, would see a stereoscopic  
7 image of that portion 27L of the scene 27.

8 In the embodiment depicted in FIG. 3, the screen 22 of camera 13 also is provided with a  
9 center slit 25C, which, when shutter 22 opens to allow light from the scene 27 to enter the camera  
10 13, allows a center region 26C of the image recording medium 21 to record what is depicted in FIG.  
11 3 as region 27C of the scene 27. It will be appreciated that the center region 26C is a direct view of  
12 the region, and the ray 28C approximately corresponds to the optical center of the camera.

13 As noted above, the images recorded by the camera 13 at successive steps around the center  
14 of rotation of the mast 14 can be mosaiced together by the panorama mosaic image generator 12 to  
15 provide left and right panorama images. The left and right panoramic images, when viewed  
16 simultaneously by an observer, in particular by the observer's left and right eyes, results in a  
17 stereoscopic panoramic image of the panoramic scene centered on the center of rotation of mast 14.  
18 The manner in which the left and right panoramic images are generated will be described in detail  
19 in connection with FIG. 4. With reference to FIG. 4, each of the images 30(1) through 30(N)  
20 (generally identified by reference numeral 30(n)) recorded at "N" (where "N" is an integer)  
21 successive steps around the center of rotation of the mast 14 includes a left image portion 30L(n) and  
22 a right portion 30R(n). The left image portion 30L(n) of each image 30(n), in turn, corresponds to  
23 the left region 26L as recorded on the image recording medium 21 at the "n-th" step, and the right  
24 image portion 30R(n) corresponds to the right region 26R as recorded on the image recording  
25 medium 21 at the same "n-th" step. The panorama mosaic image generator 12 receives the  
26 successive images 30(1), 30(2), ..., 30(N) and mosaics the left image portions 30L(1), 30L(2), ..., 30L(N)

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1 therefrom together to form the left panoramic image 31L, as indicated by the arrows 32L(1),  
2 32L(2),...32L(N). Similarly, the panorama mosaic image generator 12 mosaics the right image  
3 portions 30R(1), 30R(2),...30R(N) therefrom together to form the right panoramic image 31R, as  
4 indicated by the arrows 32R(1), 32R(2),...32R(N). The panorama mosaic image generator 12 can  
5 generate the left and right panoramic images 31L and 31R using any conventional technique for  
6 mosaicing images or portions of images together. It will be appreciated that the left and right  
7 panoramic images 31L and 31R conform to what an observer would see through his or her left and  
8 right eyes, respectively, as they revolve through the left and right viewing circles 5L and 5R  
9 described above in connection with FIG. 1B. The panoramic mosaic image generator 12 can  
10 generate the left and right panoramic images 31L and 31R as respective image strips, or it may form  
11 the images as respective continuous loops by mosaicing together their respective left and right ends.  
12 In addition, the images may be formed on or stored in any convenient medium, such as paper or film,  
13 in digital form in electronic or magnetic data storage, or other media as will be appreciated by those  
14 skilled in the art.

15 It will further be appreciated that the widths of the left and right image portions 30L(n) and  
16 30R(n) of the respective images 30(n), which are generally related to the widths of the left and right  
17 slits 25L and 25R in the screen 22 (FIG. 3), will generally determine the angle to which the motor  
18 16 will be constrained for successive steps. The angle between successive steps will be such as to  
19 ensure that the successive image portions 30L(1), 30L(2),...30L(N) can be mosaiced together to  
20 provide a single and continuous left panoramic image 31L and the successive images 30R(1),  
21 30R(2),... 30R(N) can be mosaiced together to provide a single and continuous right panoramic  
22 image 31R.

23 As noted above, in one embodiment, the screen 22 (FIG. 3) also has a center slit 25C to  
24 facilitate recording of a portion of the scene 27 in a center region 26C of the image recording  
25 medium, the portion being intermediate the portions recorded on the left and right regions 26L and  
26 26R. The center image portions as recorded on the respective images 30(n) are identified in FIG.

1 2 by reference numeral 30C(n). In that case, the panorama mosaic image generator 12 can also  
2 generate a center panoramic image from center image portions 30C(n) of the successive images  
3 30(n). While the center panoramic image so generated (which is not depicted in FIG. 4, may be used  
4 for stereo viewing together with one of the other two panoramic images 31L and 31R, it is preferable  
5 to use the left and right panoramic images 31L and 31R since the symmetry between the two images  
6 reduce distortion and increase stereoscopic disparity.

7 The distance of the camera 13 from the mast 14, as well as the separation between the left  
8 and right slits 25L and 24R, are selected such that for normal stereoscopy the radius of the viewing  
9 circle to which all rays 28R, 28L are tangent, approximates the distance between a person's eyes,  
10 which, in turn, approximately corresponds to the diameter of the viewing circle described above in  
11 connection with FIG. 1A. It will be appreciated that, the diameter of the viewing circle can be  
12 enlarged or reduced for exaggerated or reduced stereo.

13 With this background, operations performed by the stereoscopic panorama recording and  
14 generating system 10 in connection with generating the left and right panoramic images 31L and  
15 31R will be described in connection with the flow chart in FIG. 5. With reference to FIG. 5, after  
16 the camera rig 11 has been positioned such that the axis of mast 14 is placed at the center of rotation  
17 for the stereoscopic panorama, the motor control 17 initially enables the motor 16 to position the  
18 camera 13 at a starting point at which the first image 30(1) will be recorded (step 100). After the  
19 camera 13 is appropriately positioned, the motor control 17 notifies the panorama mosaic image  
20 generator 12 (step 101).

21 Thereafter, the stereoscopic panorama recording and generating system 10, in a number of  
22 iterations, records successive images 30(1), 30(2),... 30(N) at successive steps around the center of  
23 rotation of mast 14. In each iteration, the panorama mosaic image generator 12 controls the camera  
24 13 to record an image, in the first iteration image 30(1), on the image recording medium 21 (step  
25 102). In that operation, the panorama mosaic image generator 12 can enable the camera shutter 23  
26 to open to facilitate exposure of the image recording medium 21. After the image recording medium

12

1 21 has been suitably exposed, the shutter 23 will be closed. Thereafter, if the camera 13 uses film  
2 as the image recording medium 21, the film can be advanced. Alternatively, if the camera 13 uses  
3 a CCD array as the image recording medium 21, the panorama mosaic image generator 12 can  
4 enable the image to be stored by a storage medium (not shown) maintained by the camera 13, or  
5 downloaded to it (that is, the panorama mosaic image generator 12) for storage.

6 After the image has been recorded by the image recording medium 21 in step 102, the  
7 panorama mosaic image generator 12 will determine whether all of the images 30(1) through 30(N)  
8 used in generating the left and right panoramic images 31L and 31R for the stereoscopic panorama  
9 image pair have been recorded (step 103). If the panorama mosaic image generator 12 makes a  
10 negative determination in step 103, that is, if it determines that all of the images 30(1) through 30(N)  
11 needed for the stereoscopic panorama image pair have not been recorded, it will enable the motor  
12 control 17 to, in turn, control the motor 16 to advance a step (step 104). Thereafter, operations return  
13 to step 102 to facilitate recording of another image 30(2).

14 The stereoscopic panorama recording and generating system 10 performs steps 102 through  
15 104 through a plurality of iterations, in each iteration recording an image 30(n) at each successive  
16 step around the center of rotation of mast 14, until the panorama mosaic image generator 12  
17 determines in step 103 that all of the images 30(1) through 30(N) needed for the stereoscopic  
18 panorama image pair have been recorded. At that point, the panorama mosaic image generator 12  
19 can begin processing the recorded images 30(n) to generate the stereoscopic panorama image pair.  
20 In that operation, the panorama mosaic image generator 12 can initially identify the left and right  
21 image portions 30L(n) and 30R(n) for the respective images 30(n) (step 105) and mosaic successive  
22 left image portions 30L(n) to form the left panoramic image 31L and the successive right image  
23 portions 30R(n) to form the right panoramic image 31R (step 106). The panorama mosaic image  
24 generator 12 generate the left and right panoramic images 31L and 31R in step 106 using any  
25 convenient mosaicing technique.



1 Although the stereoscopic panorama recording and generating system 10 described above  
2 in connection with FIG. 2 makes use of a single camera mounted on mast 14 and arm 15 and rotated  
3 by the motor 16 and motor control 17 through the arc required to generate the panoramic image of  
4 the scene 27, other arrangements may be used. For example, rather than using a motor controller,  
5 the rotation of the mast can be approximated by measuring image motion from the video frames  
6 using computer vision techniques. As another example, FIG. 6 schematically depicts a second  
7 embodiment of the system, identified by reference numeral 50, in which a number of cameras are  
8 mounted in a circle. It will be appreciated that, preferably, the diameter of the circle is selected in  
9 the same way as the rotating camera system described above in connection with FIG. 2, that is, so  
10 that the rays from the left slits and the rays from the right slits of all cameras should be tangent to  
11 an inner viewing circle, which will correspond to the diameter of the viewing circle 5 described  
12 above in connection with FIG. 1A. The cameras can record the images of the scene  
13 contemporaneously, and thereafter the images can be processed to generate the left and right  
14 panoramic images in the same manner as that described above in connection with FIG. 4. With  
15 reference to FIG. 6, the stereoscopic panorama recording and generating system 50 includes a  
16 plurality of cameras 51(1) through 51(N) (generally identified by reference numeral 51(n) supported  
17 by a circular support 52. The number "N" of cameras will correspond to the number required to  
18 generate the number "N" of images 30(N) required to provide the left and right image portions  
19 30L(n) and 30R(n) sufficient to generate the left and right panoramic images 31L and 31R. The  
20 cameras 51(n) may be similar to the camera 13 (FIG. 2) used in stereoscopic panorama recording  
21 and generating system 10 described above in connection with FIGS. 1 and 2. Each of the cameras  
22 51(n) will have a particular field of view 52(n) represented by the dashed lines 52L(n) and 52R(n),  
23 and arrow 53(n). The number of cameras "N," their respective field of views 52(n) and their  
24 disposition around circular support 52 will be sufficient to ensure that sufficient numbers of left and  
25 right image portions 30L(n) and 30R(n) will be recorded to ensure that the left and right panorama  
26 images 31L and 31R are continuous.

1 In the systems 10 (FIG. 2) and 50 (FIG. 6), the cameras 13 and 51(n) were described as either  
2 pinhole cameras or cameras with lenses for focusing the images from the scene 27 onto the image  
3 recording medium 26. In other embodiments, described in connection with FIGS. 7 through 9  
4 mirrors are used to reflect images of the scene 27 toward the camera. FIGS. 7 through 9  
5 specifically depict, in schematic form, the image recording components (essentially analogous to the  
6 camera rig 11 depicted in FIG. 2) for respective stereoscopic panorama recording and generating  
7 systems, and do not depict the panoramic mosaic image generator 12 which also be included in such  
8 a system. With reference initially to FIG. 7, that FIG. schematically depicts a top view of a camera  
9 rig 60 including a multi-sided CCD array 61 and a mirror array 62. In one embodiment, the CCD  
10 array 61 is multi-sided, as seen from the top, with each side 60(1) through 60(S) (generally identified  
11 by reference numeral 60(s)) having two CCD devices 61(s)(L) and 61(s)(R) (generally identified by  
12 reference numeral 61(s)(l/r)). In the illustrative embodiment depicted in FIG. 7, the CCD array 61  
13 is in the form of an octagon, as seen from the top, in which case "S" equals "eight." As noted above,  
14 FIG. 7 depicts the CCD array 61 from above, and it will be appreciated that, a side 60(s) will  
15 preferably, when viewed from the front, have a square or rectangular configuration, as shown in FIG.  
16 7A. Similarly, each of the CCD devices 61(s)(l/r) will preferably have a square or rectangular  
17 configuration when the respective side 60(s) is viewed from the front. Preferably the CCD devices  
18 61(s)(l/r) on each side 60(s) will be symmetrically disposed on opposite sides of a vertical line 63  
19 that vertically bisects the respective side 60(s).

20 Displaced from each side 61(s) of the octagonal CCD array 61 is a respective mirror 64(s),  
21 with each mirror 64(s) comprising left and right mirror faces 65(s)(L) and 65(s)(R) (generally  
22 identified by reference numeral 65(s)(l/r)) which are generally disposed at a predetermined angle  
23 with respect to each other, with the vertex 66(s) pointing towards the center of the respective side  
24 60(s) of the CCD array 61, and parallel to the vertical line 63 that vertically bisects the respective  
25 side 60(s). The respective mirror face 65(s)(l/r), is disposed to direct an image of a portion of a  
26 scene towards the correspondingly-indexed CCD device 61(s)(l/r).

1 The left and right mirror faces 65(s)(L) and 65(s')(R) ( $s'=s+1$ , modulo S), of proximate  
 2 mirrors of proximate mirrors 64(s) and 64(s') serve to direct images of a scene for recording by the  
 3 respective left and right CCD device 61(s)(L) and 62(s')(R). This will be apparent from the  
 4 following. Generally, as shown in FIG. 7, respective rays 70(s)(L) and 70(s')(R) from a scene (not  
 5 shown) are reflected from the respective mirror faces 65(s)(L) and 65(s')(R) toward the respective  
 6 CCD devices 61(s)(L) and 61(s)(R). It will be apparent that the rays 70(s)(L) and 70(s)(R) are  
 7 generally from the left and right directions of a portion of a scene. Thus, the image as recorded by  
 8 the combination of the CCD device 62(1)(L) and 62(2)(R), as provided by the respective mirror faces  
 9 65(1)(L) and 65(2)(R) will comprise the appropriate left and right images for a particular region of  
 10 a scene.

11 The images recorded by successively-indexed CCD devices 61(s)(L) are mosaiced together  
 12 to provide a left panoramic mosaic image. Similarly, the images recorded by successively-indexed  
 13 CCD devices 61(s)(R) may be mosaiced together to provide a right panoramic mosaic image.

14 FIG. 8 depicts a plan view, as seen from the top, of image recording components comprising  
 15 a camera rig 80 for a stereoscopic panorama recording and generating system which makes use of  
 16 a single fixed camera and a rotating planar mirror. With reference to FIG. 8, the camera rig 80  
 17 includes a camera 81 and a planar mirror 82. Camera 81 is generally a conventional camera. Mirror  
 18 82 will typically be mounted on a vertical post (not shown) and rotated by motor (also not shown)  
 19 in a manner similar to the manner in which camera 13 and arm 15 are rotated by motor 16 and motor  
 20 control 17, as described above in connection with FIG. 2. The mirror 82 will preferably be in  
 21 rectangular form, the top edge of which is depicted in FIG. 8. The mirror 82 reflects an image from  
 22 a scene 83 toward the camera 81 along a line indicated by dashed line arrow 84. Since the image  
 23 provided to the camera 81 is a reflected one, the virtual point of view, or center of projection, of the  
 24 camera is defined by the dashed line arrow 85. As the mirror is rotated, the portion of the scene 83  
 25 which is reflected toward the camera rotates around a circle centered on the center of rotation of the  
 26 mirror of which directed virtual point of view of the camera 81 moves around the circle 86. As the



1 mirror 82 is rotated, the camera 81 records a series of images, similar to images 30(n) described  
2 above in connection with FIG. 4. A panoramic mosaic image generator can mosaic together left and  
3 right image portions of the images to generate left and right panoramic images, in a manner similar  
4 to that described above in connection with FIG. 4.

5 Since the image provided to the camera 81 is a reflected one, the virtual point of view, or  
6 center of projection, of the camera is defined by the dashed line arrow 85. As the mirror is rotated,  
7 the portion of the scene 83 which is reflected toward the camera rotates around a circle centered on  
8 the center of rotation of the mirror of which directed virtual point of view of the camera 81 moves  
9 around the circle 86. As the mirror 82 is rotated, the camera 81 records a series of images, similar  
10 to images 30(n) described above in connection with FIG. 4. A panoramic mosaic image generator  
11 can mosaic together left and right image portions of the images to generate left and right panoramic  
12 images, in a manner similar to that described above in connection with FIG. 4.

13 FIG. 9 depicts a plan view, as seen from the top, of image recording components comprising  
14 a camera rig 10 for a stereoscopic panorama recording and generating system which makes use of  
15 a single fixed camera and a curved mirror. With reference to FIG. 9, the camera rig 100 includes a  
16 camera 101 and a curved mirror 102. Camera 101 is a conventional camera, such as a conventional  
17 film or video camera. The mirror 102 will preferably have a curved reflective surface, as depicted  
18 in FIG. 9. The mirror 102 is curved so as to reflect an image from a scene 105 toward the camera  
19 101 along rays indicated by dashed line arrows generally indicated by reference numeral 104.  
20 Generally, the mirror 102 is constructed, and the camera 101 is placed, so that rays from the scene  
21 105, are directed to the optical center of the camera as indicated by reference numeral 106. In that  
22 process, light rays reflected from the scene, and projected tangent to an imaginary viewing circle  
23 103, will reflect off the mirror 102 and be directed towards the optical center of the camera. The  
24 camera 101, in turn, is located so as to receive and record the image represented by the light rays  
25 passing through the optical center. It will be apparent that the curved mirror 102 facilitates the

1 recording of an image of scene 105 that subtends a relatively wide angled arc, generally up to  
2 approximately 180 degrees.

3 Camera rig 100 may be fixed, in which case it will record images of only the scene 105 as  
4 shown in FIG. 9. To cover a full 360 degrees, an illustrative embodiment may use six such camera  
5 rigs, with three of the rigs being used to cover 360 degrees for the left eye and three being used to  
6 cover 360 degrees for the right eye. Alternatively, camera rig 100 may be mounted to rotate a center  
7 of rotation centered on the imaginary viewing circle 103. Any convenient support (not shown) may  
8 be provided to support the camera 101 and mirror 102. The support will be is mounted on a vertical  
9 post (not shown), with the assembly being rotated by motor (also not shown), all in a manner similar  
10 to the manner in which camera 13 and arm 15 are rotated by motor 16 and motor control 17, as  
11 described above in connection with FIG. 2. As the assembly is rotated, the camera 101 records a  
12 series of images, similar to images 30(n) described above in connection with FIG. 4. A panoramic  
13 mosaic image generator can mosaic together left and right image portions of the images to generate  
14 left and right panoramic images, in a manner similar to that described above in connection with FIG.  
15 4.

16 As noted above, the invention also provides arrangements by which a panoramic mosaic  
17 image generator, such as generator 12, can generate panoramic stereoscopic image pair using  
18 computer graphics techniques. Operations performed by the panoramic mosaic image generator in  
19 this connection will be described in connection with FIG. 10. Generally, the panoramic mosaic  
20 image generator synthesizes images for cameras located on a circle 110. For normal stereoscopic  
21 effects, the radius of the circle 110 should be on the order of the radius of the human head, and the  
22 angle "a" should be such that  $d=2r \sin a$  approximately corresponds to the distance between human  
23 eyes. If angle "b" approximately corresponds to angle "a," at every position on the circle 110, an  
24 image is synthetically generated in two viewing directions, one for the left panoramic image 31L and  
25 the other for the right panoramic image 31R, as shown in FIG. 10. As shown in FIG. 10, the viewing  
26 direction at each camera position P1, P2,..., is to the right for the image to be used in generating the



1 left panoramic image 31L and to the left for the image to be used in generating the right panoramic  
2 image 31R. All of the images generated at the successive camera positions are mosaiced together  
3 to create the left and right panoramic images.

4 The invention is further directed to systems for displaying the left and right panoramic  
5 images 31L and 31R (FIG. 4) generated by the panoramic mosaic image generator 12 to a viewer,  
6 thereby to enable the viewer to view the panorama represented thereby stereoscopically. Several  
7 illustrative panoramic image display systems will be described in connection with FIGS. 11 through  
8 12B. With reference to FIG. 11, that FIG. schematically depicts a panoramic image display system  
9 120 which includes goggles which a viewer may wear over his or her eyes. Generally, the  
10 panoramic image display system 120 includes left and right display devices 121L and 121R, a  
11 display control module 122, left and right display controllers 123L and 123R and a pointing stick  
12 124. The left and right display devices 121L and 121R may be worn by the viewer as goggles over  
13 the respective left and right eyes. The left and right display devices 121L and 121R may comprise  
14 any convenient devices, including, for example, thin-film-transistor active matrix display devices,  
15 liquid crystal devices, and the like. The left and right display devices 121L and 121R may be  
16 mounted in any convenient arrangement which will hold them in front of the viewer's respective  
17 eyes, including, for example, spectacle frames, masks and the like. The left and right display  
18 controllers 123L and 123R, under control of the display control module 122, enable the respective  
19 left and right display devices 121L and 121R to display at least selected portions of the respective  
20 left and right panoramic images 31L and 31R, so that they may be viewed by the viewer. The  
21 display control module enables the left and right panoramic images will be aligned so as to display  
22 images relating to the same portion of the panorama at the same relative position in the viewer's field  
23 of vision, as described above in connection with FIG. 1B. The viewer can use the pointing stick 124  
24 to control the display control module to adjust the particular portion of the scene that is directly in  
25 front of the viewer's eyes, which is similar to controlling the angular position of an observer in  
26 viewing the scene as described in connection with FIG. 1A.

1 Since the geometrical shape of the surface on which the panoramic image is recorded may  
2 be different from the geometrical shape of the surface on which the image is displayed, some  
3 geometrical transformation on the image may be needed to avoid distortions. For example, the  
4 rotating camera system of FIG 2 generates the panoramic stereo image on a cylindrical surface.  
5 When the image is displayed using goggles having flat screens, the image should preferably be  
6 rectified using a cylinder-to-plane transformation before the display. On the other hand, no  
7 rectification may be needed when the cylindrical image is displayed on a cylindrical theater as in  
8 FIG 11A.

9 FIGS. 12A and 12B schematically depict an omni-directional theater arrangement for  
10 displaying a stereoscopic panorama to a viewer, with FIG. 12A generally depicting a plan view and  
11 FIG. 12B depicting a top view. In the arrangement depicted in FIGS. 12A and 12B, the left and right  
12 panoramic images 31L and 31R are projected onto the surface of a cylindrical screen so that they are  
13 visible by a viewer positioned interiorly of the space subtended by the screen. The images may be  
14 polarized in orthogonal directions, and a viewer, positioned interiorly of the space subtended by the  
15 screen and wearing polarized glasses, can view the panoramic image on the screen stereoscopically.  
16 The images comprising the respective left and right panoramic images 31L and 31R may be  
17 projected by projectors located within the space subtended by the screen, or from locations external  
18 thereto. Since the images are polarized orthogonal to each other, the polarization of the lenses of the  
19 glasses worn by the viewer will allow each of the viewer's eyes to receive a respective one of the  
20 images projected onto the screen.

21 Thus, and with reference to FIGS. 12A and 12B, an omni-directional theater 140 includes  
22 a cylindrical screen 141 and a plurality of projector sets 142(1) through 142(N) (generally identified  
23 by reference numeral 142(n)), each including two projectors 143L(n) and 143R(n). Each of the  
24 projectors 143L(n) and 143R(n) in each projector set 142(n) projects a portion of the respective left  
25 and right panoramic images 31L and 31R onto a respective portion of the screen 141. The number  
26 of projection sets 142(n) is preferably selected so that the images as displayed will not be distorted,

1 and the portions of the left and right panoramic images 31L and 31R that are displayed by the  
2 respective projector sets 142(n) will be such as to provide continuous images around the screen 141,  
3 thereby to provide a panoramic image. The projector sets 142(n) may be positioned to project their  
4 images onto the exterior of the screen 141 as shown in FIG. 12B, provided the screen 141 is such  
5 as would allow the projected images to be viewed interiorly of the space subtended by the screen  
6 141. Alternatively, the projector sets 142(n) may be positioned to project their images onto the  
7 interior of the screen 141. A viewer 144, standing interiorly of the space subtended by the screen  
8 141, wearing polarized glasses 145, will be able to view the panoramic image stereoscopically.

9 It will be appreciated by those skilled in the art that, in addition to the use of polarization,  
10 stereo viewing can be done using any other method of stereo separation. This includes stereo glasses  
11 with shutters, which work in accordance with alternating display of "left" and "right" images. The  
12 glasses have fast shutters, which are transparent at the left eye, while opaque at the right eye, when  
13 the left image is displayed, and the opposite when the right image is displayed. Another arrangement  
14 is the use of "Anaglyph Stereo" with green-red glasses.

15 The invention provides a number of advantages. In particular, the invention provides  
16 systems and methods for generating stereoscopic panoramic images of a scene, and for displaying  
17 the images to an observer in a manner so that the viewer can view the panoramic images  
18 stereoscopically.

19 It will be appreciated that a number of modifications may be made to the systems and  
20 methods as described herein. For example, although the system described in connection with FIG.  
21 2 has been described as providing left and right panoramic images by enabling the camera 13 to  
22 rotate around a fixed point, it will be appreciated that the system may instead enable the camera 13  
23 to translate along a line, thereby to provide for an elongated panoramic image.

24 In addition, although the systems as described herein have been described as recording and  
25 displaying a static panoramic image, it will be appreciated that the systems may be used to record

21

1 and display motion pictures stereoscopically. For example, systems such as those described in  
2 connection with FIGS. 6 through 8, which do not make use of a revolving camera, mirror or the like,  
3 can be translated as necessary along a path and record 360° panoramic images as they are translated.  
4 Systems such as those described in connection with FIGS. 2, and 8, which do make use of a  
5 revolving camera, mirror or the like, can also be translated while they are being revolved. However,  
6 in the latter case, it will be appreciated that, to provide a complete panorama, the camera and/or  
7 mirror will need to be translated as well as revolved. The camera and/or mirror can be revolved  
8 through a complete 360° circle before it is translated slightly and the operation repeated.  
9 Alternatively, if the translation is relatively slow, so that there is a substantial overlap so as to allow  
10 for a fairly complete panorama as the camera and mirror is translated, they may be translated while  
11 one or both are revolved. In either case, it will be appreciated that the panoramic mosaic image  
12 generator 12 generate a series of left and right panoramic images 31L and 31R, which can be  
13 successively displayed to a viewer. For example, the panoramic image display system 120 will  
14 enable the left and right display devices 121L and 121R to display the successive left and right  
15 panoramic images. Similarly, in the omni-directional theater arrangement 140, the left and right  
16 projectors 143L(n) and 143R(n) of the respective projector sets 142(n) will be enabled to project  
17 respective portions of the left and right panoramic images 31L and 31R on respective portions of the  
18 screen 141. It will be appreciated that the advancement of left and right panoramic images the left  
19 and right display devices 121L and 121R, and by projectors in the various projector sets, an as  
20 among the various projector sets, will be synchronized manner so that left and right images 31L and  
21 31R as displayed will be from the same panorama.

22 In addition, although the camera 13 has been described as including a screen 22 having left  
23 and right slits 25L and 25R , it will be appreciated that a camera 13 need not include a screen.  
24 Instead, the panoramic mosaic image generator may use sections from the respective left and right-  
25 hand portions of the images 30(n) in generating the respective left and right panoramic images 31L  
26 and 31R.



1 In addition, although the panoramic image display system 120 has been described as making  
2 use of a pointing stick to control the angular position of the center of the stereo panoramic image  
3 relative to the viewer's eyes, it will be appreciated that other devices may be used, including, for  
4 example, arrangements such as trackers for determining changes in the position or angular  
5 orientation of the viewer's head.

6 Furthermore, although the invention has been described as including an arrangement for  
7 recording images for use in connection with generation of the left and right panoramic images 31L  
8 and 31R, which may be displayed to a viewer, it will be appreciated that the left and right panoramic  
9 images 31L and 31R may instead be generated using computer graphics techniques.

10 It will be appreciated that systems constructed in accordance with the invention may find  
11 utility in a number of applications, including, for example, recording of sporting events for later  
12 reporting or analysis, during travel, and for use in education and marketing. In addition, systems  
13 constructed in accordance with the invention may find utility in connection with robotics and  
14 computer video games. Furthermore, although the invention has been described in connection with  
15 specific display arrangements, it will be appreciated that other types of arrangements, such as display  
16 on computer monitors, televisions and the like may also find utility.

17 It will be appreciated that a system in accordance with the invention can be constructed in  
18 whole or in part from special purpose hardware or a general purpose computer system, or any  
19 combination thereof, any portion of which may be controlled by a suitable program. Any program  
20 may in whole or in part comprise part of or be stored on the system in a conventional manner, or it  
21 may in whole or in part be provided in to the system over a network or other mechanism for  
22 transferring information in a conventional manner. In addition, it will be appreciated that the system  
23 may be operated and/or otherwise controlled by means of information provided by an operator using  
24 operator input elements (not shown) which may be connected directly to the system or which may  
25 transfer the information to the system over a network or other mechanism for transferring  
26 information in a conventional manner.



1           The foregoing description has been limited to a specific embodiment of this invention. It will  
2 be apparent, however, that various variations and modifications may be made to the invention, with  
3 the attainment of some or all of the advantages of the invention. It is the object of the appended  
4 claims to cover these and such other variations and modifications as come within the true spirit and  
5 scope of the invention.

6           What is claimed as new and desired to be secured by Letters Patent of the United States is: